Future of Security of Supply

Initial Research for National Grid DSO

January 2026

UNIVERSITY OF BATH

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Executive summary

This report summarises the results of National Grid Electricity Distribution innovation project 'Future of Security of Supply: Initial Research' funded via the Network Innovation Allowance funding mechanism.

Security of supply refers to the ability of the electricity system to deliver power to customers reliably and safely, both in normal operating conditions and during faults, maintenance, or after external disruptions. For electricity distribution networks in Great Britain (GB), this is governed by a broad landscape of standards, incentives, and regulations. At its centre sit *Engineering Recommendation P2 (EREC P2)*, which defines minimum security and restoration requirements, and *Engineering Report 130 (EREP 130)*, which provides the accompanying compliance and cost-benefit methodology.

Although P2 has been updated several times since its introduction in 1952, the fundamental structure of the standard continues to reflect the assumptions and analysis established in P2/5 (1978). The convention used for version of standards is the use of / followed by the version number. These assumptions include the presence of a predominantly passive distribution network, homogeneous customer needs, predictable peak electricity demand, and limited distributed generation. A significant proportion of customers' energy usage is currently met by other sources such as gas and petroleum products.

However, the electricity system has changed dramatically in recent years and is expected to change further, due to several key factors:

- **The electrification of heat, transport and industry** is increasing the volume and criticality of electricity demand, creating larger cold-load pickup and heightening societal dependence on uninterrupted supply.
- **Digitalisation** means that power interruptions now quickly affect communications, payments, health devices, industry processes and commercial activity.
- **The distribution network itself is transitioning to an active, flexible system**, with growing volumes of distributed generation (DG), storage, demand-side response (DSR) and low-carbon technologies (LCTs), alongside greater automation and observability.

These developments expose important limitations in the current security-of-supply standards landscape. Existing standards:

- Assume customers are broadly homogeneous in behaviour, flexibility and the value they place on supply interruptions (Value of Lost Load (VoLL)).
- Apply deterministic planning thresholds based solely on estimated group peak demand – an increasingly uncertain metric in a system rich with DG, storage and DSR which lacks an equivalent operating standard.
- Treat DG, storage and flexibility as non-firm, limiting their allowable contribution to security (e.g., dominance tests).
- Do not reflect modern voltage and reactive power requirements in distribution networks and flexible customers' ability to respond to network constraints, such as voltage excursion.
- Treat input/planning standards (e.g., P2, EREP 130) and output measures (e.g. the Interruptions Incentive Scheme (IIS), Worst-Served Customers) as separate mechanisms rather than a cohesive whole-system security framework.
- Display significant divergence from transmission operation and planning standards, despite the increasing convergence between the characteristics of the two systems.

Given the scale of electrification and the transition to more active network operation, a review of distribution security-of-supply standards is now essential, as recognised by the Government and the wider industry in view of:

- New opportunities to understand and meet customers' diverse need for security of supply.
- Increasing network operability and intelligence through the adoption of automation, digitalisation and the use of flexibility, which have changed the nature of the security of supply risk, as well as the network ability to dynamically response to network issues.

- Flexibility markets continuing to mature and flourish as energy consumers adopt greater volumes of LCTs and respond to new opportunities and incentives to participate.
- The rise of data and digitalisation allowing network security of supply performance and customer service performance to be measured in greater granularity, providing timely information to coordinate between DNOs, suppliers, aggregators and the system operator. Collectively, they will provide new capability and confidence for DNOs to make greater use of flexibility to manage network constraints, offset network investments and improve customer services.

This report identifies a set of potential future security-of-supply options:

1. Output Standards (Customer-facing reliability outcomes)

- *Enhance the Interruptions Incentive Scheme (IIS)* to better reflect modern customer expectations and the increasing diversity of customer needs.
- *Increase the granularity of VoLL*, potentially varying by customer segment, technology adoption, or contract type – improving the alignment between customer's perceived value and reliability investment signals.

2. Planning Standards (Investment & reinforcement requirements)

- *Update the deterministic P2 standard*, modernising group classifications, treatment of DG/ES/DSR, and assumptions around maintenance, cold load pickup, and flexibility services.
- Move towards *probabilistic security standards*, building on international practice (e.g. Victoria, Australia) to better reflect risk, uncertainty and cost-effectiveness.

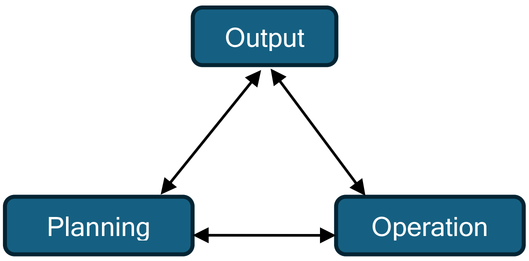
3. Operating Standards (Real-time system operation)

- *Introduce a distribution operating standard*, providing clear expectations for real-time use of flexibility, operational security margins, and coordination with NESO.
- *Develop standards for DG, storage and demand-side services*, including firmness definitions, availability requirements and interoperability.
- *Strengthen voltage and reactive power standards*, potentially moving to probabilistic voltage planning and creating an explicit reactive power envelope.

4. Whole System Alignment

- *Highlight the limits of network capabilities* to allow customers to plan for extreme emergency events and encourage customer responses in terms of operation and investment.
- *Reflect year-round conditions in standards*, considering the contribution of DG, energy storage and DSR.
- *Improve alignment between transmission and distribution network standards* in terms of the treatment of flexibility, peak and year-round conditions and the use of existing assets considering flexibility characteristics and coincident behaviour.

Planning and operating standards affect the output seen by connected customers; the outputs seen give feedback to how planning and operating standards are developed and implemented.



The report recommends:

- Making *Short-term Improvements to Deterministic Planning Standards* by reassessing the dominance test that restricts the contribution from DG, energy storage and DSR; requiring that network capacity under intact conditions is sufficient; and expressing demand groups in terms of customer numbers rather than peak demand.
- Gaining *a Deeper Understanding of Customer Needs* by analysis of the stakeholder engagement that network companies already undertake. This may need additional stakeholder engagement to cover any missing stakeholder segments.
- Carrying out *Option Development and Engagement* using the customer needs to build on the options identified in this report.
- *Introducing Operating Standards* to deliver safe and efficient network operating envelopes under year-round conditions.
- Developing *Greater Alignment with Transmission Standards* at distribution in planning, operating and performance standards. This should simplify the treatment of flexibility.

Overall, the report highlights that the current distribution security-of-supply framework, while historically successful, has not kept pace with the scale of electrification, digital dependency and newly available system flexibility. The options and recommendations presented form potential pathways toward a modernised and customer-focused set of future standards that maximise the use of existing and new assets, and engineer a smarter, digitally driven flexible future network. Achieving this will enable DNOs to navigate the increasingly complex and rapid-changing energy landscape, to deliver high quality of supply to society's increasing dependency on electricity, and ensures supply reliability, resilience and affordability in a net-zero future.

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1. Introduction

What is security of supply?

Security of supply refers to the ability of the electricity system to deliver power reliably and safely, both in normal conditions and during disturbances. It can be understood through four dimensions:

- **Adequacy:** Having enough generation and network capacity to meet peak demand.
- **Continuity:** Minimising the frequency and duration of customer interruptions.
- **Resilience:** Withstanding or recovering quickly from equipment failures, extreme weather, or fuel shortages.
- **Safety**: Maintaining supply without endangering people or damaging equipment.

A key challenge is aligning system design and operation with the level of reliability and quality of service that customers expect.

How do we measure security of supply?

IEEE 1366-2022 [1] provides guidelines for defining and calculating reliability indices. Whilst there are several reliability indices, the main ones used are:

- **System Average Interruption Duration Index (SAIDI):** Total duration of interruption for the average customer during a predefined period of time.
- **Customer Average Interruption Duration Index (CAIDI):** Average time required to restore service.
- **System Average Interruption Frequency Index (SAIFI):** How often the average customer experiences a sustained interruption over a predefined period of time.
- **Momentary Average Interruption Frequency Index (MAIFI):** Average frequency of momentary interruptions.

In GB, via the Interruptions Incentive Scheme (IIS), Ofgem set targets for DNOs for security and availability of supply to demand customers as follows:

- **Security of supply** – number of supply interruptions as a percentage of customers connected in a year. Referred to as Customer Interruptions (CI) but equivalent to SAIFI, and
- **Availability of supply** – average number of minutes that a customer has their supply interrupted. Referred to as Customer Minutes Lost (CML) but equivalent to SAIDI.

P2 is a network-facing standard, and hence does not use these measures. P2 measures security in terms of circuit redundancy generally referred to as N-1 (sufficient remaining network capacity following a single outage), N-1-1 (a fault outage during a maintenance outage) or N-2 (two fault outages at the same time).

2. History and landscape of security standards in GB

While engineering recommendation (EREC) P2 (system planning security standard) [2] and engineering report (EREP) 130 (guidance on the application of EREC P2) [3] form the core, dedicated security-of-supply standards for electricity distribution, they are part of a much wider framework of standards. Figure 1 illustrates this broader GB security-of-supply landscape and how P2/EREP130 interact with the wider set of standards and obligations. The following sections explore the history of P2 and explore how other related standards, legislation and regulations impact security of supply.

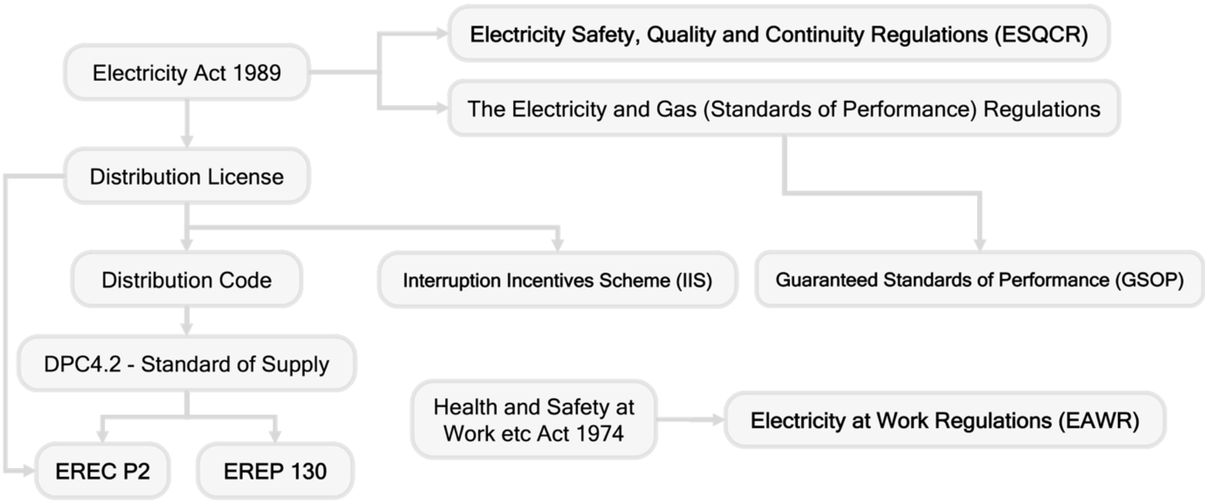

Figure 1 - GB security of supply landscape for electricity distribution.

History of P2

Engineering Recommendation P2 defines the minimum level of security and restoration capability for a network and is an input-based standard. P2 has a long history shown in Figure 2. In total, there have been eight versions of P2, with the ninth currently being written. The convention used for version of standards is the use of / followed by the version number. While some versions presented minor updates, other versions of P2, such as P2/3, P2/5, P2/6 and P2/7, contained more significant changes. These changes were driven by either a desire to improve system reliability (P2/3), improve the economic rationale (P2/5) or changes to the technology connecting to the network (P2/6 and P2/7). From P2/5 onwards, it was accompanied by a guidance document which is process-based and explains how to assess compliance. The security requirements are for groups of two or more demand customers. The requirements get progressively more onerous as the size of a group, measured in MW, increases.

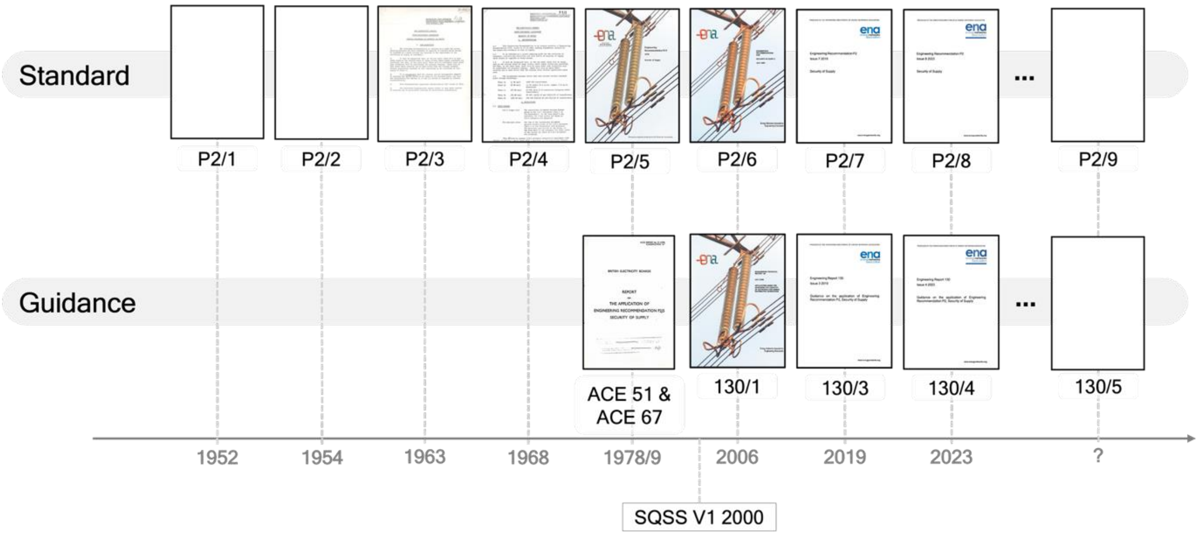

Figure 2 - History of the versions of P2 and supporting guidance documents. The first version of SQSS for transmission networks is also marked on the timeline to show when transmission standards diverged from distribution standards.

Early versions

First two versions of P2 (P2/1 and P2/2) were basic without any specified restoration times and no consideration of coincident outages. P2/3 included the 400 and 275kV, made partial provision for two circuit outages, introduced maximum times for restoration, the use of auto-reclose on 11kV networks and limiting the use of transformers to nameplate capacity for planning purposes.

P2/5

P2/5 introduced economic and reliability calculations to review and restructure Table 1 – the normal levels of security required classified in demand groups. The 132kV network was transferred from transmission to distribution during the 1970s but there were still several older fossil-fuelled power stations connected at that level. P2/5 introduced the contribution to security that could be expected from these fossil-fuelled power stations. The standard was accompanied by ACE51 (Report on the application of engineering recommendation P2/5 security of supply) which detailed reliability calculations and the calculation of the value of lost load (VoLL), although it did not calibrate Table 1 to a particular VoLL. There was recognition that rural networks performed worse that urban and ACE67 (Report on reliability investment in radial HV distribution systems with overhead lines) was also published showing the benefits on 11kV rural networks of auto-reclose, pole mounted reclosers, fuses and interconnection.

P2/5 was adopted at privatisation as a licence requirement and Table 1 was incorporated into section 3 of SQSS (National Electricity Transmission System Security and Quality of Supply Standard) when SQSS was created from six existing standards at the transmission level.

P2/6

P2/6 [4] completely revised the contribution of generation to security of supply identifying the contribution that renewable forms of generation can provide. It was accompanied by ETR130/1 [5] (Application guide for assessing the capacity of networks containing distributed generation) and ETR131 (A user guide for an analysis package for assessing generation security capability).

In 2007, Ofgem introduced a self-derogation process to P2/6 for parts of the network where group demand was up to 60MW. It allowed distributors to self-derogate where reinforcement was planned but not yet completed but did not derogate from the financial consequences of a loss of supply greater than that required under P2. This was extended several times until the introduction of P2/7.

P2/7

P2/7 [6], via EREP 130/3 [7], introduced a supplementary Cost-Benefit Analysis allowing the assessment of whether remedial works are not economically justifiable and/or do not align with its asset management strategy. This was introduced to enable the self-derogation process, introduced in 2007, to be withdrawn. The CBA should consider network losses and the cost of supply interruptions to customers using a VoLL of £17,000/MWh or a different value were deemed appropriate by the DNO. Whilst ACE51 demonstrated the calculation of VoLL, Table 1 of P2 has not been calibrated to a VoLL. This was the first time a value of VoLL has been introduced into P2.

P2/7 also updated the contribution to demand security from generation and extended this assessment to the contribution from storage and demand side measures.

P2/8

P2/8 [2] made a minor amendment to Table 1 to include the option of reduced security of supply for specific class of supply B demand groups.

P2/9

Is currently under development and is looking to address the treatment of imports to energy storage installations.

Other related standards, legislation and regulations

P2 and 130 ensure design adequacy. While they may not directly address *operational reliability*, *customer service*, or *real-time resilience*, they are key steps to achieving these. The following sections explore the other standards, legislation and regulations that sit within the security of supply landscape.

Electricity Safety, Quality and Continuity Regulations

The Electricity Safety, Quality and Continuity Regulations (ESQCRs) [8] are statutory regulations made under the *Electricity Act 1989* [9]. They ensure that electricity networks are safe, reliable, and fit for continued operation, protecting both people and property while maintaining continuity and quality of supply. Two regulations (Reg 3 and Reg 23) are directly applicable to security of supply.

Regulation 3

Reg 3 covers the general adequacy of electrical equipment. It requires that all electrical equipment is:

- Sufficient for its purpose and operating conditions.
- Constructed, protected, and maintained to prevent danger and interruption of supply, as far as reasonably practicable.

It emphasises both safety and network reliability and places duties on distributors and generators to assess risks (vandalism, flooding, etc.) and mitigate accordingly. This regulation gives an obligation not to exceed equipment ratings which could result in equipment failure affecting security of supply.

Regulation 23

Reg 23 covers precautions against supply failure. It requires DNOs to ensure networks are:

- Arranged and protected (via fuses, automatic switching, etc.) to limit the number of consumers affected by faults.
- Operated to avoid interruptions of supply as far as reasonably practicable.

Reg 23 also introduces an obligation to design networks with resilience and selectivity, preventing cascading failures. The guidance notes to reg 23 [10] of the ESQCRs specifically refer to compliance being demonstrated by compliance with P2/5. Failure to comply with ESQCR carries liability on conviction of a fine not exceeding level 5 on the standard scale – an unlimited fine.

Obligations in the Guaranteed Standards of Performance (GSOP)

The GSOP payments are what an electricity distribution network operator must pay if they fail to meet specified standards of performance [11]. Many of the GSOP standards are relevant to security of supply, including restoration times, the provision of new connections and quotes, customer service and voltage quality. Hence, the GSOP payments provide both a financial and reputational incentive.

Obligations in the Electricity at Work Regulations (EAWR)

The main applicable provision to security of supply in the EAWR is *Regulation 5*, referring to strength and capability of electrical equipment [12]. In the context of outages within those defined in Table 1 of P2, the standard reflects this requirement in:

- **para 3.2**: *"The appropriate continuous rating or cyclic rating or, where it can be satisfactorily determined, the appropriate emergency rating…"*
- and **para 5.2**: *"A circuit should not be loaded to a point where it would suffer unacceptable loss of life"*

Outages beyond those in P2 Table 1 are credible and so suitable mitigations such as running arrangements or protection schemes are needed to ensure compliance with the EAWRs. These requirements are similar to those in reg 3(1) of the ESQCRs.

Obligations in the Interruptions Incentive Scheme (IIS)

While IIS does not contain any requirements on DNOs, instead, it sets incentives to encourage both investment and improved operational performance for customer minutes lost and customer interruption that are greater than 3 minutes [13]. It also sets requirements to report on less than 3-minute interruptions and customers experiencing multiple interruptions.

Across England and Wales distributors performance in the period between 1991/92 till 2002/03 was that interruptions/100 customers stayed roughly constant and customer minutes lost increased by nearly 10%. IIS was introduced in 2002/03 and comparing performance from 2002/03 till 2023/24 shows that interruptions/100 customers decreased by over 40% and customer minutes lost by over 50% showing the impact of IIS.

IIS has been calibrated using a VoLL of £21,000/MWh (at 2018/19 prices) which is an inflated value from the London Economics Report (2013) on VoLL [14]. The value in that report, £17,000/MWh, has been incorporated in the CBA process described in EREP 130. Ofgem has stated that it intends to update VoLL for ED3 [15].

Provisions for Worst-Served Customers (WSC)

A worst served customer is defined as:

> *Customers facing experiencing 12 or more higher voltage (HV+) unplanned interruptions over a three-year period, with a minimum of two higher voltage unplanned interruptions each year. For the purposes of the Ofgem WSC programme, interruptions are power cuts that last longer than 3 minutes.*

The WSC mechanism is a regulatory mechanism under RIIO-ED2 designed to improve service for customers who experience significantly more power interruptions than average [16]. It does this through a "Use-It-or-Lose-It" allowance to fund WSC improvement schemes. As the number of WSC is small, this is more of a reputational incentive than a financial or compliance issue.

Priority Services Register (PSR)

The PSR is a free service run by energy suppliers and network operators to provide help to customers who may need additional support – permanently or temporarily [17]. Whilst the PSR does not have a direct effect on the security of supply, it provides help during emergencies or power cuts and advance notice of planned outages (where possible).

Comparisons

Understanding the security of supply in (i) the actively managed transmission system, (ii) other sources of energy and (iii) those in other parts of the world, provide insights into the issues that need to be considered.

Security of Supply for Electricity Transmission in Great Britain

The core, dedicated security standard for electricity transmission in Great Britain is the Security and Quality of Supply Standard (SQSS), currently at version 2.10. Overall, SQSS is broader in scope, integrating generation, operation, and voltage management [18], while P2 is narrower, focusing on distribution-level network design security. The differences between SQSS and P2 are highlighted as follows:

- **Generator connections** – SQSS defines planning criteria for connecting one or more power stations. P2 does not include generation connection criteria and only recognises that DG/DSR contribution may be lost through ANM, control or protection failures. Due to single circuit connections combined with ANM, many generators have a low level of connection security that was not considered when P2/6 was created.
- **Operating standard** – SQSS sets minimum operational security levels for prevailing load. This includes demand groups and embedded generation contributions. For lower demand groups, it follows the structure and requirements of P2/5 (including contribution from embedded small and medium fossil-fuel-based power stations).
- **Voltage criteria** – SQSS specifies planning and operational voltage limits, and allowable step changes. At the distribution level, voltage limits are set via ESQCR (for customer connections) and ER P28 (for step changes), rather than prescribing them within P2.

P2/8 and EREP 130 have evolved to better reflect a decarbonised, flexible distribution system, while SQSS remains anchored in legacy P2/5 assumptions. SQSS section 3 – *Demand Connection Criteria (Onshore Transmission System)*, is based on P2/5 for lower demand groups and has not been updated in line with later P2 revisions. Hence, SQSS does not reflect modern contributions from distributed generation, storage, or demand-side services.

In addition, P2 & EREP 130 provides guidance on latent demand and cold load pickup, differentiating between contracted vs. non-contracted resources and an economic assessment framework for compliance (absent in SQSS). However, P2 does not specify whether demand should be met under intact network conditions whereas SQSS requires demand to be met. Inconsistencies between P2 and SQSS creates a risk of disputes between DNOs and NESO over compliance expectations.

Security of supply for other energy sources

A significant amount of energy used by customers is from fuels other than electricity. Decarbonisation requires a substantial substitution of these fuels with electricity and hence comparison with the security of these sources is important.

All fuels, including electricity, are subject to the Energy Act 1976 [19] where the government can regulate or prohibit the production, supply, acquisition or use of the fuels. This is focused on energy sources rather than a physical network.

In gas distribution, the *Transporter Standard Licence Condition 16* [20] require capacity to be adequate to supply the gas customers consume. There are no specified redundancy requirements, however there are also GSOPs and various health and safety requirements.

With oil and petroleum products there is considerable security of distribution due to the competitive market. Where standards exist, they are focused on physical security.

Electricity distribution security of supply in other areas of the world

Overall, information on security of supply standards for electricity distribution networks outside GB is scarce. However, several existing reviews were used to build a better picture of international security of supply. The *"SQSS Fundamental Review – Initial Benchmarking"*, published in 2009, compared the treatment of SQSS in France, Spain, Ireland, USA, NZ, Chile, Belgium and Japan [21]. The review found that there is a wide range of VoLL used between nations: £1.4k/MWh (Chile) → £30k/MWh (UK). This variation in VoLL around the world, illustrated in Figure 3, was further highlighted in the 2018 CEPA report titled: *"Study on the Estimation of the Value of Lost Load of Electricity Supply in Europe"* [22] commissioned by ACER. VoLL is further explored in Section 3.

No respondents to the survey carried out by the SQSS Fundamental Review provided security based on P2 approach of banding demand groups which imposes more onerous requirements as the size, in MW, increases [21]. Instead, they favour CBA or N-1 for all demand group sizes. In addition, the survey found that jurisdictions predominantly used deterministic planning standards (typically N-1/N-2/N-1-1) to ensure network security.

The report *"Approaches to setting electric distribution reliability standards and outcomes"* was commissioned by the Australian Energy Market Commission (AEMC), undertaken by The Brattle Group in 2012 [23]. It compared distribution reliability regulation in Australia, New Zealand, Great Britain, Netherlands, Italy, New York and California. While most jurisdictions were found to use deterministic planning standards (typically N-1 or N-2) to ensure network security, Victoria state, Australia, was an exception, opting to use a probabilistic planning approach. The report also noted increasing use of performance-based incentives (e.g., SAIDI, SAIFI, and customer compensation) rather than prescriptive input standards.

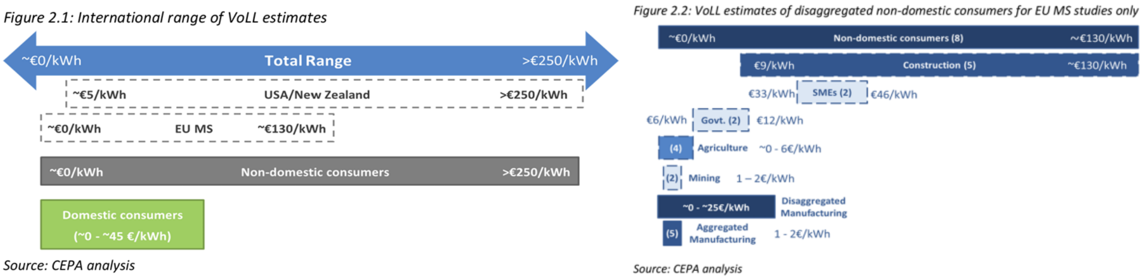

Figure 3: CEPA analysis of VoLL around the world [22].

3. Trigger points for changing security of supply standards

Transitioning to a net-zero energy system at pace and scale requires DNOs to enhance network operability, maximise the use of existing assets, and engineer a smarter, more flexible distribution network of the future. This is required to meet rising electricity demand and growing renewable generation while containing network costs and improving customer services.

The distribution system is becoming more complex. New electric transport and heat devices, alongside rapid growth in data centres, are driving society and the economy's increased dependency on electricity. The growth of storage and DG on the customers' side of the meter adds to the complexity of managing the network. At the same time, DNOs face increased uncertainty about where and how future demand and distributed resources may connect, and whether they will be compatible with existing infrastructure. This exposes DNOs to risks in pro-active investment.

However, these changes also create new opportunities:

- **Granular understanding of customer needs:** Data and digitalisation provide a richer picture of customers' diverse security of supply requirements. High-granularity data enables more accurate monitoring of security-of-supply performance and customer service, supporting more seamless coordination between DNOs, suppliers, aggregators, and the system operator.
- **More intelligent networks:** Automation, digitalisation and system flexibility are transforming how system security risks manifest and help improve the network's ability to respond dynamically to issues.
- **Maturing flexibility markets:** As customers adopt more low carbon technologies, flexibility markets will continue to flourish and expand, creating new opportunities for managing constraints and supporting system security.

Collectively, these developments provide new capability and confidence for DNOs to make greater use of flexibility to manage network constraints, optimise delivery of network investments and improve customer service.

While the current distribution security standards, which have been incrementally adapted over time, have served GB customers well, they now require review and modernisation to reflect: (i) society's growing dependence on electricity, (ii) the increasing intelligence of the distribution network, and (iii) the rising potential for customer-driven flexibility as we decarbonise.

Specific drivers for change

Society has an increasing dependency on electricity supply driven by a combination of economics (in the technology), regulation and customer choices to lower their carbon footprint.

- **Electrification of transport** – Rapid EV uptake increases overall demand, as transport migrates from the use of petrol and diesel, and creates potential coincidence peaks but also introduces flexibility opportunities through smart and vehicle-to-grid charging. Figure 4 shows the EV uptake in the UK to date [24].
- **Electrification of heat (and cooling)** – Growth in electric heating, as heating migrates from gas, raises cold-pickup risks after outages and shifts winter demand patterns, while offering new thermal storage flexibility potential. The growth in central heating in the UK is shown in Figure 5 [25]. The mix of main fuel type used in central heating systems of UK households is shown in Figure 6 [26].
- **Electrification of Industry** – Industrial decarbonisation through electrification is increasing demand concentration and dependency on supply resilience.
- **Digital dependency** – Communications, data centres, commerce, and public services are critically dependent on continuous electricity supply—short interruptions now have wider economic and societal impacts.

- **Distributed generation** – most DG is connected at single circuit risk and significant volumes are controlled by active network management systems. Whilst historically loss of DG had little impact on the security of supply, and system frequency control by NESO, the risk associated with the loss of large volumes of DG now needs to be considered.

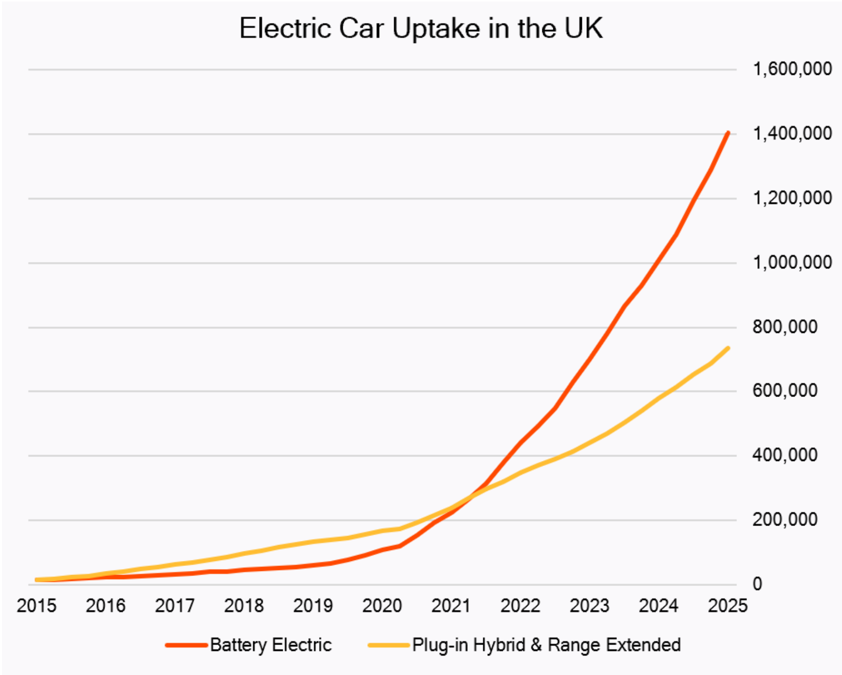

Figure 4: Electric car uptake in the UK to date [24]

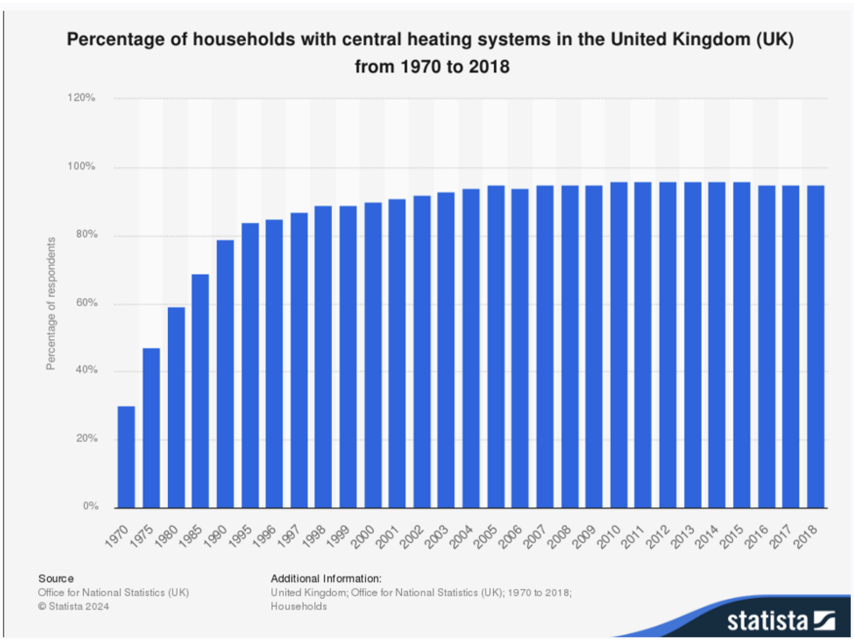

Figure 5: Growth in central heating in the UK [25].

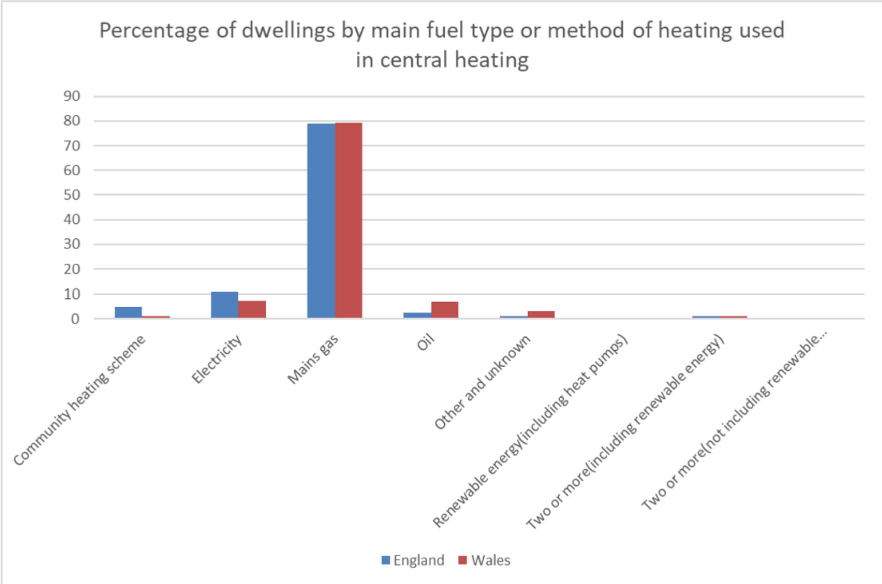

Figure 6: Current fuel type or method of central heating in the UK [26].

Current treatment of demand and its impact on security of supply

The core demand security standard for electricity distribution (Table 1 in P2) has remained essentially unchanged from P2/5, issued in 1978. Meanwhile, electricity use, electrification, and customer dependency have transformed radically, whilst Table 1 was calibrated with customers' usage and requirements in 1978. As the security requirements in P2 are driven by group demand, energy efficiency improvements will increase the number of customers within a demand group and there is growing difficulty in observing true group peak demand as flexibility, storage, and DG reshape load patterns.

IIS has been highly successful in incentivising DNOs to exploit opportunities in driving up the quality of customer services from leveraging growing network operational capability arising from digitalization and smart controls by the retrofitting of remote-control and automation. Progress has slowed as these capabilities have been exploited and further improvements, generally requiring additional network, are significantly more expensive.

Value of lost load (VoLL)

Whilst Table 1 of P2 is not calibrated to a VoLL, it is an economic measure of the investment that customer attribute to their electricity supply. VoLL is generally estimated using willingness-to-accept and willingness-to-pay surveys and hence is dependent on customer perceptions, particularly where respondents have not experienced a powercut, or where the timing or duration of a powercut caused them little inconvenience. Hence, it is affected by the time of day, time of year, duration, and frequency of interruptions. It also varies significantly by customer type and generally increases with increased duration and frequency.

Wide-spread electrification increases the socioeconomic need for reliable electricity supplies. It also increases the disparity between customers' needs for security of supply, and their level of response to extreme events. The same extreme event will impact on energy customers in the same area differently, the degree of their understanding on the limits of the supply system, and the degree of automation and response they could afford. Studies from ENW's VoLL investigation (ENW is now part of Scottish Power Energy Networks) suggest that society's dependency or the value they placed on electricity supply increases as more LCTs connected to the system [27].

A "one-VoLL-fits-all" no longer reflect the increasing diversity in customer technologies, usage patterns and flexibility. Given the difficulty of assessing the absolute value of VoLL it's most powerful use maybe in comparing the consistency across generation, transmission and distribution assessments or between investment options.

There is some consistency in how VoLL is applied across the current system. Under the Electricity Market Reform (EMR) framework, the Loss of Load Expectation (LOLE) is derived using a VoLL of £16,940/MWh together with a Cost of New Entry (rental rate of marginal peaking plant) of £47.18/kW [28]. Similarly, EREP 130 uses a VoLL of £17,000/MWh for the CBA approach for variations from P2 requirements [3].

Two of the most recent pieces of published research on VoLL are:

- London Economic (2013) "The Value of Lost Load (VoLL) for Electricity in Great Britain" [14] and
- NIA project led by ENW assisted by Third Party Collaborators Impact Research and Frazer-Nash Consultancy [27].

RIIO-ED2 methodology decision (17/12/2020) set a value of VoLL to calibrate IIS by updating VoLL in line with inflation to £21,000/MWh (in 2018/19 prices) to reflect customers' expectations around security of supply and the importance of maintaining high levels of network reliability.

From passive to active electricity distribution networks: why an operating standard might be needed

Historically, distribution networks were designed for passive loads and unidirectional power flow from transmission to customers. Ensuring that there was sufficient capacity to meet peak demand was generally sufficient for year-round reliability.

Today, distributed generation and energy storage fluctuate with weather and market signals. Active customer participation, via dynamic tariffs and other flexibility services, (EVs, heat pumps, PV) adds variability to both load and generation. As a result, distribution networks are now dynamic systems requiring continuous operational management, not just capacity planning. Existing planning standards (like P2) focus on peak demand.

An operating standard would define minimum security and flexibility requirements throughout the year, ensure reliability under variable, bidirectional, and flexible network conditions and support safe integration of DERs and active demand management.

Prior research and calls for change

National Infrastructure Commission's report on Electricity Distribution

The report

As part of a 2025 report titled: "*Electricity distribution networks: Creating capacity for the future*" [29], the National Infrastructure Commission (NIC) set out several recommendations for ensuring that Britain's low-voltage electricity networks can keep pace with rising demand.

Recommendation 2 from the report was for the UK government and Ofgem to review security of supply standards for distribution networks to ensure that they are designed for future loads and vulnerable customers are protected. More specifically, as part of business planning for the next price control:

- Ofgem should require DNOs to identify 'no regrets' activities that would improve security of supply.
- The government and Ofgem should work with DNOs to agree the detailed work required to review security of supply standards and how this will be undertaken.

The recommendation concludes with a call for a full review of security of supply standards to be completed by the end of 2028.

The government's response

The UK government responded by agreeing with the NIC recommendation but believed it may not be completable by 2028 [30]:

> *"The government agrees with this recommendation, electricity security of supply and the continued reliability of distribution networks is a priority for government as we transition to Clean Power 2030 and beyond."*

It also highlighted the growth of flexibility and the need for greater LV data, the importance of continuing with the Interruptions Incentive Scheme (IIS) and consideration should be given to the impact of an increase in severe weather occurrences and required interruptions from increasing capacity build when setting the IIS during the next price control.

Ofgem's response

Ofgem responded to the NIC report in their ED3 Sector Specific Methodology Consultation (SSMC) [15] where they did not see dealing with the NIC's concerns as a security of supply issue but one of forecasting the growth in low carbon technologies.

An important part of the ED3 SSMC relates to flexibility. Ofgem's consultation outlines a commitment to support the "*DSO's responsibility to procure and dispatch flexibility services efficiently, ensuring they are used to complement strategic network development.*" The consultation goes on to say that distributors should:

> *"Use flexibility services to manage intermittency, network operations and local constraints, while ensuring that flexibility is not used as a substitute for necessary long-term network investment."*

The SSMC also highlighted voltage and losses optimisation as being potentially relevant to a security of supply standard:

- **Voltage Optimisation** – *"Voltage optimisation is a key operational responsibility for DSOs, helping to maintain power quality, reduce energy consumption, and improve system efficiency. This objective ensures DSOs are actively managing voltage levels to deliver consumer and system benefits."*
- **Losses Optimisation** – *"Losses optimisation includes broader strategies such as network configuration, asset design, and operational control. This objective ensures DSOs are minimising technical losses to reduce costs and environmental impact."*

Ofgem emphasises the importance of these techniques in contributing to lower system costs and improved reliability.

IEEE Standards

Whilst they do not call for change to security standards, IEEE standards for smart grids relevant to security and quality of supply are:

- **IEEE 2030.11-2021** – IEEE Guide for Distributed Energy Resources Management Systems (DERMS) Functional Specification [31].
- **IEEE 1547-2018** – IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces [32].
- **IEEE 1366-2022** – IEEE Guide for Electric Power Distribution Reliability Indices [1].
- **IEEE 1250-2018** – IEEE Guide for Identifying and Improving Voltage Quality in Power Systems [33].
- **IEEE C57.123-2019** – IEEE Guide for Transformer Loss Measurement [34].

BEIS (now DESNZ) Electrical Engineering Standards Review, 2020

This review [35] recognised that in P2/7 some of the built in redundancy in P2 can be used to support additional load growth without investment. It highlighted that reliability is currently better than P2/7 requires largely attributed to IIS. It also notes that there appears to be a discrepancy between the VoLL underpinning P2 and that of IIS and that a single value of VoLL is not appropriate. It says:

> *"Research shows that VoLL could be much more usefully expressed as a number of values for different customers and different uses of energy, and in all cases as an increasing monotonic function of time."*

Whilst it is correct to say that both P2 and IIS have economic analysis, creation of Table 1 from P2/5 (that is largely unchanged) did not have a specified VoLL and the application document ACE51 published supporting it only refers to comparing the cost per kWh saved between competing solution proposals and not an absolute value.

The standards review report also highlights concerns around potential conflicts in provision between P2 and SQSS:

"P2/7 specifically allows substitution between services from customers and the capability of network assets to secure demand. The Panel is concerned that SQSS does not easily or formally permit the same equivalence and this should be reviewed … Finally the Panel notes that the differences between SQSS and P2 cause distortions across the transmission/distribution interface, both in terms of optimising system performance and in the commercial treatment of connecting generation to the two system."

Royal Academy of Engineering report on "Counting the cost: the economic and social costs of electricity shortfalls in the UK"

As part of the conclusions of this report [36] the authors state that:

"There is wide variation in estimates of VoLL, meaning that no concrete conclusions can be made on the cost of electricity shortfalls from existing research. It is very important to note that VoLL is not a value-neutral measure; it is a measure of people's perceptions of the value of a unit of electricity."

It is also emphasised that:

"estimates of VoLL in £/MWh appear very high when compared against the average wholesale or retail price for electricity".

EU Smartgrids Security and Resilience Task Force - White Paper 2016 on "The need for a fundamental review of electricity networks reliability standards"

This white paper [37] summarised the work that Imperial College carried out for the ENA P2 working group in 2016, highlighting that the VoLL implied by the deterministic requirements in P2 was significantly higher than the VoLL from the London Economics report (2013) [38] and highlighting further benefits that could be achieved using demand side measures to support system security. The white paper recommended that:

"…the philosophy of the existing electricity distribution and transmission network reliability standards should be reviewed. Probabilistic framework can support the development of secure and efficient electricity network reliability standard in the context of the delivery of an efficient low carbon electricity system."

The report also recommended and highlighted the following:

- A review of voltage limits – allowing a lower voltage under emergency conditions.
- More guidance on asset replacement risk.
- Long term design to include network losses (LV cables capacities 4 to 8 times peak demand).
- A higher net capacity would provide for enhanced coordination of DG, DSR and storage across large regions facilitating a cost-effective real-time demand-supply balance and control of network flow.
- Long-term loss-inclusive network design is expected to increase the network redundancy at the distribution networks, while the controllability provided by distributed technologies at the distribution networks may reduce the need for redundancy at the transmission network level.

Current limitations in the security of supply standards landscape

Review and assessment are needed of the role of flexibility and distribution operation in enhancing customer services and network security, recognising:

- The criticality of supply security for different customers and different uses of energy, thus the relevance of a single VoLL to inform different customer needs for supply security.
- A lack of consistent and complete information and metrics to measure the range of customer interruption to inform targeted interventions, innovation and incentives.
- The growing use of network operability and customer flexibility to manage year-round network constraints in addition to system peak.

- The need for greater compatibility and alignment between customer standards, distribution and transmission standards, and operating and planning standards to drive a whole-system approach that leads to better customer services at a lower cost.

Figure 7 provides a graphical summary of the security of supply standards landscape, from the perspective of customers, the network and the whole system. The following sections explore the limitations of these components of the current security of supply landscape.

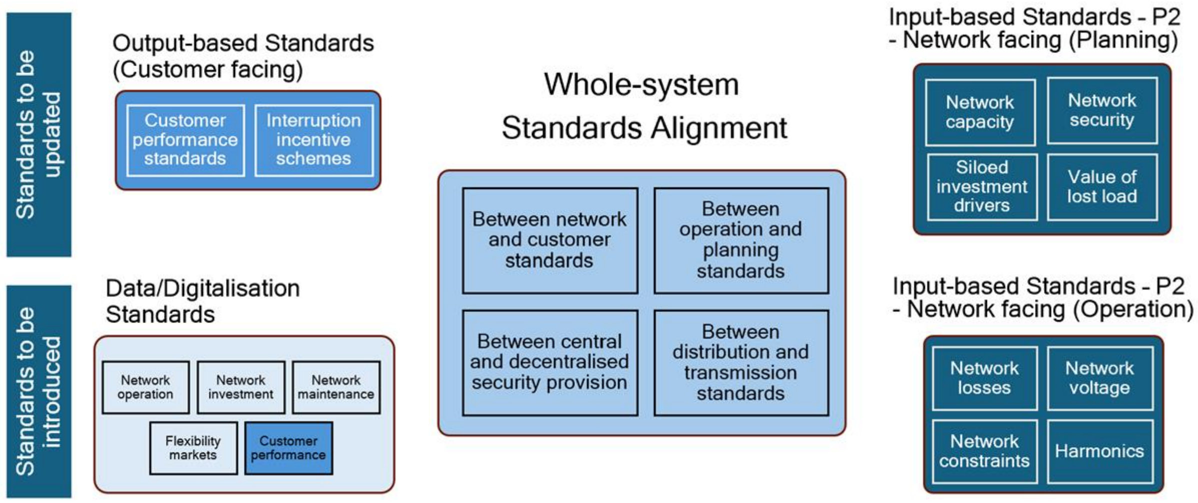

Figure 7: Standards landscape.

Customer-facing Standards

Customer Services

- **Customer service performance standards**: The performance measures of customer service quality, such as Customer Interruptions (CI), Customer Minutes Lost (CML) and Worst Served Customers (WAC), as well as vulnerable customers, have not recognised the changes in customer technologies, behaviours and increasing network operability. This limits DNOs ability to capture a full range of customer interruptions to devise targeted interventions, reducing disparity in customer performance across difference network areas.
- **Interruptions incentive scheme (IIS):** The IIS has been successfully in driving up the quality of customer services from greater network interventions, however, it has failed to keep up with a smarter grid with growing ability to manage local network congestions and constraints to suit customer choices.

Network-facing Standards

Network planning

- **Network capacity**: Network capacity is primarily driven by peak demand and assumes that adequate network capacity for peak demand is sufficient for year-round conditions. This may not support the import/export requirements throughout the year to drive net zero transition.
- **Demand security:** Despite the considerable and continued changes in customer technologies, behaviours and flexibility, the demand security standard to meet customers needs has largely remained unchanged from P2/5 issued in 1978. P2 has not kept up with the needs for supply security of future customer, customer classes, and their increasing divergent technology adoptions, priorities and coincidences. The security resulting may be under or over specified for a given group of customers
- **Value of loss load**: A single VoLL does not reflect the diversity of customer needs.

Network operation

- **Active network operation**: DSOs now have increased network operability to manage network congestions, voltages and losses, and support safe integration of DERs and flexibility. There are however no operational standards like their transmission counterparts to manage network conditions on day-to-day basis to manage risk and make a better use of existing local flexible resources and increased network operability.

Whole-system Standards

Compatibility and alignment of standards

- **Sub-system approach**: There are loose links between customer performance standards and network security standards, and between system planning standards and operation. This limits the understanding and interactions between DNOs, energy customers and key stakeholders to effectively address network operational issues and share the responsibility when the security of supply is at risk. This drives up costs and risks.

Asset Visibility and Data sharing

- **Data Sharing:** There is limited real-time information to allow effective coordination between DNOs, suppliers, aggregators, the National Energy System Operator (NESO) and other third parties. There is a lack of consistent and complete information on the operational characteristics and performance of DERs connected to their networks. There is a lack of granular customer performance information to target WSC or vulnerable customers.

4. Options that should be considered

High-level principles to option development

Development of options has considered several broad principles to keep up with the changes in emerging customer technologies, increasing network intelligence/automation, markets/opportunities for flexibility and clean energy:

- **Deeper insights into customers' needs:** standards for network planning and operation and customer products must meet the current and future customers' diverse needs.
- **Efficiency:** Move away from one-size-fits-all demand supply standards to greater customisation allowing valuable resource targeting areas that matter most to customer requirements and network conditions.
- **Shared responsibility:** The security standards enable energy customers to understand the limit of the grid supply from extreme events and to respond if there are cheaper, quicker flexibility options. It also informs manufacturers to design LCTs that offers system support when they are under stress.
- **Whole system:** The security standards must align distribution network security with: (i) the service performance that customers require, (ii) network operation and investment, (iii) distribution and transmission supply standards.
- **Digitalisation:** The security standards will be upgraded or introduced from granular evidence based on customer performance reporting (locational-specific actions) and network conditions.
- **Agile security standards:** Able to adapt to the rapidly changing energy landscape, especially through deep transformation needed to deliver net zero.

More general principles to option development for engineering standards, presented in The Electricity Engineering Standards Review [35], were also considered. These principles are highlighted in Figure 8.

From	To
Incoherent and inconsistent mix of customer output performance, network investment standards, and a large body of network industry standards	Performance based standards at end user level, connected to performance-based standards at licensed entity level. Open systems and interoperability
One-size-fit-all customer service standard	Customised customer service standards
Deterministic, accounts for limited system conditions and variability in asset failure rates	Probabilistic, account for multiple system conditions and varied asset conditions
Embodiment of legacy learning from the industry's first century, reactive to change in energy customers and greater intelligence in systems	Future facing - Embracing and enabling Clean Power 2030 and beyond, where obsolete learning removed, best international practice adopted
Focused on electricity as a silo within the energy system, not the whole system	Whole electricity system focus (G,T,D, users), with awareness of other vectors
Closed, rigid review processes, relies on consultancy studies	Open, Agile review processes based on emergent learning and open platform to reduce the time and cost for consensus and change
Network operators are the sole responsible party for supply security	Devolving responsibilities to consumers and communities so consumer choice drives development
Responsibility and accountability of are often vague	Clear hierarchy/purpose of ownership and accountability between Ofgem and industry parties for design, implementation and ongoing performance/suitability

Figure 8: General principles from the Electricity Engineering Standards Review [35].

What should a distribution security standard cover?

Currently the distribution security standard only considers network capacity at the planning stage. There are other aspects that influence the security and quality of supply, highlighted in Figure 9. Whilst some aspects of these are in separate standards, there could be benefit in combining them into one standard to ensure compatibility between the different aspects.

Security of demand (currently P2)

Should there be provisions to allow demand-side flexibility to access and support the transmission network?

With growing reliance on electricity, driven by transport and heat electrification, is there a need for higher levels of demand security?

How should demand security be assessed?

Contribution of flexibility & DG to security of demand

How conservative should the estimates of contribution from flexible devices and DG be, to ensure that sufficient support is available during operation?

Security of generation and storage

P2 treats DG/storage only as contributors to demand security—no standards exist for their own connection security.

Should we introduce standards for DG/storage connection security or limits on simultaneous DG/storage loss?

Operation of distribution network

What standard (risk) should the network be operated to in real time?

Given the developing flexibility in demand, should this be an important part of an operating standard?

Reactive power control

NESO needs to be able to control reactive power to control voltage on the transmission network - should there be limits on the requirements at GSPs?

or

Sufficient distribution capacity to allow access to reactive resources on distribution networks?

Harmonics

There are standards for harmonics caused by connections (ER G5).

Should there be limits for the harmonics on the distribution network within the security standard?

This could clarify who is responsible for ensuring that there is headroom for future connections.

Losses

How to ensure that the economic cost of losses is accounted for in the assessment of network capacity requirements?

Consistent at the transmission boundary

There must be a smooth transition at the transmission boundary (SQSS), particularly the contribution to security of distributed generation, energy storage and demand flexibility.

Figure 9: What could be in a distribution security of supply standard?

Types of potential future standards

Firstly, what is meant by a deterministic, probabilistic and output standard? In the context of electricity security of supply, **deterministic standards** typically rely on fixed, predetermined scenarios, disturbances or contingencies (e.g. the N-1 criterion). Deterministic standards use fixed input values and rules, often without considering the likelihood of a particular event. The system is either deemed secure or insecure based on a binary decision.

On the other hand, **probabilistic standards** evaluate security by attempting to quantify the risk of potential failure events. This often involves considering a range of possible operating conditions and the impact of component failures weighted by their likelihood of occurrence.

Output standards focus on the measurable service quality and performance delivered to end customers, rather than the network design.

The following sections consider the potential benefits and challenges of implementing these types of standards within electricity distribution security of supply.

Deterministic standard

The distribution security standard (P2) in GB is deterministic, setting out rules that determine the degree of redundancy needed for different demand groups (defined by their maximum demands) with set restoration times for each group.

Whilst P2 Table 1 has been continuously updated to reflect contributions from intermittent embedded generation, energy storage and demand side response to meeting demand, the core principles and the framework have remained largely unchanged since 1978. The deterministic consolidation of the standard into Table 1 makes it familiar, easy to apply and simple for external bodies to verify compliance before or after an event. P2 is referenced in the Distribution Licence, the Distribution Code, SQSS (as P2/5 as both a planning and operating standard) and the guidance to the ESQCRs (as P2/5 as an operating standard).

The assumption of demand and maximum demand have not kept up with new technologies, digital innovation and emerging flexibility markets, which could distort the network's import/export requirements throughout the year.

Limitations of a deterministic standard

There are several limitations of the currently deterministic P2 standard:

- **Uneven reliability outcomes across different networks**, resulting from redundancy levels depending only on group demand and there being no accounting for network length, mix of overhead or underground circuits, or the local environment, which influence fault rates.
- **The type of outage is mostly not considered**, with no provision for different outage/return-to-service times for fault, maintenance or construction outages.
- **Periods of low demand to facilitate maintenance are assumed to exist** for larger group demands (Classes D & E). This assumption may not hold with increasing cooling and transport demand along with both demand and network flexibility increasing. DG is seeking to reduce any curtailment of their output due to maintenance outages.
- **Small increases in forecasted peak demand can trigger major reinforcement**, especially when demand groups move into Class D or E where consideration of faults during maintenance outages need to be considered.
- **Generic guidance in EREP 130 on the use of CBA** mean that VoLL is uniform for different customers, times of day or season.

Potential changes to the current deterministic standard

There are a number of potential changes that could be made to the current deterministic P2 standard:

- **Expressing demand groups in terms of number of customers** rather than peak demand in P2 Table 1 could help to reduce distortion due to flexibility and local storage. Additional weighting might be needed to differentiate customer classes (e.g. domestic, industrial etc.) based on their usage of and reliance on electricity.
- **Reassessment of the dominance test** that restricts the extent to which DG/DSR/ES can substitute for network assets is needed. Consideration of ES at domestic premises could be introduced, as well as flexible devices such smart charging EVs where charging regimes are known and controllable. This could include treatment of vehicle-to-grid (V2G) as it becomes more established.

- **Introducing an explicit requirement that network capacity under intact conditions is sufficient** could enhance the availability of embedded flexibility to the System Operator.

It is worth noting that updating deterministic standards often requires probabilistic evidence. However, the economic rationale behind P2/5's original Table 1 is poorly documented. Therefore, ensuring consistency between old deterministic requirements and new probabilistic methods is challenging and requires an open and transparent process. Changes to the current deterministic standard are likely to be an evolution and hence not significantly disruptive.

Probabilistic standard

A probabilistic reliability assessment requires data on the:

- Outage rate of each asset on the network being considered (both fault and maintenance)
- Loading of the asset
- Duration of the outage for repair
- Return to service time for an asset switched out on maintenance

The calculations, needed to assess the expected energy not supplied, are described in detail in ACE51 which accompanied P2/5. Combining this with a VoLL gives a value that can be compared with the cost of reinforcement to reduce the expected energy not supplied. Where the cost of reinforcement is below the total VoLL then reinforcement should be undertaken.

Opportunities with implementing a probabilistic standard

A probabilistic standard offers several opportunities to modernise the assessment of security of supply, making it more reflective of real-world system behaviour, customer diversity, and emerging flexibility. These opportunities include:

- Potentially **more cost-reflective and efficient investment decisions**, enabling reinforcement to be targeted where it delivers the greatest net benefit. With sufficient data, this could also take into account asset condition and its effect on reliability and hence giving a more integrated approach across investment drivers.

- **The ability to incorporate customer segmentation and differentiated VoLL**. With improving data and digitalisation, VoLL could be refined to reflect differences between customers and technologies. VoLL could be:
    - Differentiated by customer type, LCT ownership and coincidence factors.
    - Linked to the type of supply contracts with specified capacity requirements.

Challenges with implementing a probabilistic standard

There are several challenges involved with implementing a probabilistic security of supply standard:

- **Limited empirical data on asset-specific fault rates**, due to high levels of reliability, mean that data is generally aggregated to classes of assets in probabilistic assessments. Assets within a class can have significantly different fault rates due to condition and surrounding environment distorting the results. Outage/return-to-service times are similarly challenged by averaging data.

- **Probabilistic network assessments are complex and time consuming**.

- **Added complexity and data requirements** making it difficult for a third parties (regulator, customers, etc.) to check or make their own assessment of compliance.

- Under a probabilistic standard, **areas of the network with high reinforcement costs and low customer densities could have worse performance than those with low reinforcement costs and high customer densities**. Hence, it's important to consider whether customers on parts of the network with high reinforcement costs should be subjected to more frequent and longer outages or pay the true network cost. Whilst an absolute lower limit on the probability of a customer interruption could be set, this could result in very significant costs being socialised for the benefit of a small number of customers.

- **Transitioning from a deterministic to a probabilistic standard presents practical challenges.** The network would first need to be reassessed against the new criteria to quantify required investments. Agreement would then be needed on funding and implementation timescales, with appropriate derogations for parts of the network that initially fall short while compliance is phased in.

Output standard

Current limitations of output standards

Output-based standards (such as the IIS) focus on the reliability outcomes experienced by customers, measured using indicators such as Customer Interruptions (CI) and Customer Minutes Lost (CML). While they have been effective in improving overall network performance, several limitations remain:

- **There is no minimum-security backstop.** Output standards tend to provide financial incentives and penalties but do not set a guaranteed minimum level of security of supply. Ofgem has previously recognised this gap (in a 2007 letter), and therefore output standards often operate alongside a separate planning standard (e.g. P2).
- **They provide limited protection for poorly performing areas**. IIS targets apply at a company-wide level. Without additional mechanisms such as the WSC scheme, customers on weaker or remote parts of the network may continue to experience significantly worse service than the average.
- **They are benchmark-driven rather than needs-driven.** Targets are based on historic performance benchmarks so it can be difficult to determine the cost/benefit associated with performance improvements. Since DNOs can decide on the balance between investment and operating practices, there is a risk of building an investment "cliff edge" when further improvements require significant capital works.
- **Metrics do not reflect the full range of customer experiences**. Currently, the IIS does not differentiate short-duration interruptions (< 3 mins), long-duration interruptions (> 12 hours), repeated interruptions, or differences in how customers respond to outages.
- **There is limited customer differentiation.** All customers are treated uniformly despite differing impacts of electricity supply loss, flexibility levels and VoLLs.
- **Emerging data is underutilised.** Increased levels of LV monitoring and digitalisation provide access to more granular information on network performance, but current metrics and reporting methodologies do not yet exploit this capability.

Potential options for evolving output standards

There are several potential developments that could enhance the role of output standards in the security-of-supply framework:

- **Introduce more granular customer service performance metrics**, capturing wider range of interruption types, including short outages (< 3 mins), repeated outages, and long duration events (> 12 hours).
- **Increase the spatial granularity of reporting**, presenting customer service outcomes at the feeder or substation level. This would enable more targeted interventions and improve transparency for customers and stakeholders.
- **Differentiate metrics by customer type or flexibility capability**, recognising that customers with flexible devices (e.g. EVs, heat pumps, storage) may experience and value interruptions differently.
- **Evolve the IIS to include more targeted incentives**, for example incentives for fast restoration, higher incentives for long-duration outages, incentives calibrated to customer VoLL, and additional incentives for improving outcomes for WSC.
- **Clarify the role of customer-side resilience for brief interruptions**, where Uninterruptable Power Supplies (UPSs) or device-level battery support may offer more cost-effective protection than network reinforcement particularly as more customers install behind-the-meter batteries and V2G electric vehicles are adopted.

Challenges with implementing enhanced output standards

Several implementation challenges need to be considered in the case of rolling out enhanced output standards:

- Introducing granular or customer-specific metrics may make performance assessment **less transparent** for regulators and customers, and increase administrative burden.
- Effective use of granular metrics depends on **high-quality LV and customer-level data**, requiring continued investment in monitoring, data governance and interoperability.
- More granular output standards may require closer integration with P2 to avoid **conflicting drivers between planning and operational performance**.
- **Enhanced standards may raise expectations of supply continuity**. They should therefore be accompanied by clear communication about what levels of service are realistic and where customers may also need to invest in their own resilience particularly to cover low probability high impact events such as low frequency demand disconnections.

Standards for peak demand or year-round operation?

Planning or Planning and Operating Standard

Historically, the few generators embedded in the distribution network had known operating profiles or direct control by the DNO and demand connections followed established demand profiles. Construction to meet maximum demands resulted in sufficient capacity for year-round operation. Operational standards focused on system safety, operational switching for maintenance, construction and fault response together with storm or other system emergency response. Operational reconfiguration has been generally focused on reconfiguration post fault.

Operating standard – changing requirements

Transmission has a long-standing operating standard (part of SQSS) due to the active nature of the flows on the transmission system. At transmission, the operating standard is largely the same as the planning standard but at the prevailing load on the network instead of annual peak demand.

The addition of distributed generation (a significant part of which is intermittent) together with demand flexibility and storage results in the demand profile becoming more unpredictable and a need for active management of the network. Whilst IIS is an output standard that considers year-round operation, it has no backstop and applies at the overall network level rather than providing guidance on expected system operation or utilisation of existing assets.

An operating standard could develop time-varying import and export limits to ensure supply security for year-round conditions depending on the available capacity of the network at a certain time of the day. As such, it could allow a more consistent security of supply to be set for year-round conditions rather than just considering peak demand.

A potential minimum starting position would be the requirements of P2 at the prevailing load. The guidance notes to the ESQCRs imply that current compliance with regulation 23 would be tested on this basis for any significant loss-of-supply event.

Options for operating envelope standards

An operating standard develops season-varying or time-varying import and export limits to ensure supply security for year-round conditions, depending on the available capacity of the network at a certain time of the year (Figure 10). There are a range of options to balance costs, benefits, complexity and risks when introducing operational standards:

- Introducing dynamic import and export limits at the time of system peaks.
- Introducing fixed limits for a range of year-round conditions, the fixed limits vary between seasons to reflect the coincidence between DGs and between DGs and LCTs.

- Introducing dynamic limits for time of day, to further increase the temporal granularity to make the best use of the existing assets.

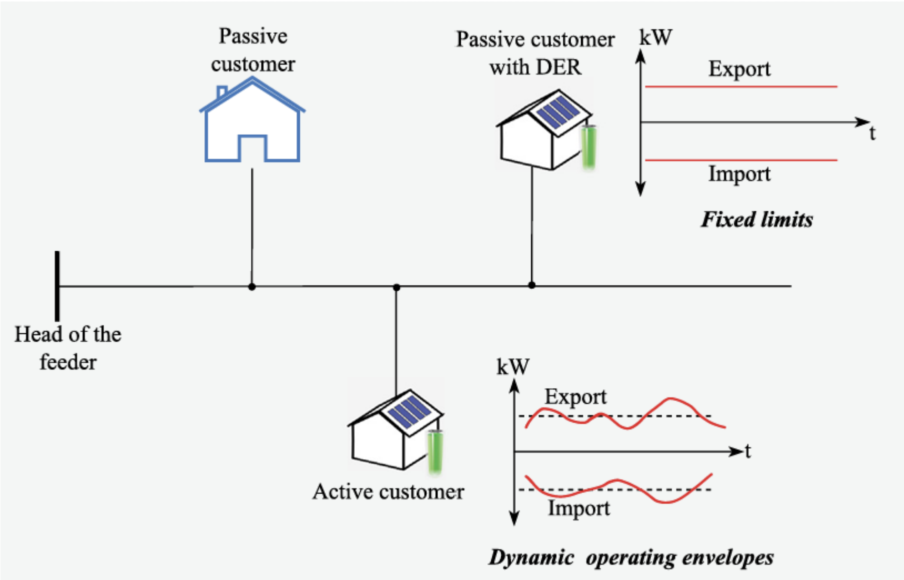

Figure 10: Illustration of operating envelopes [39].

Additional considerations

Treatment of DG/Storage/DSR

Consideration is usually given to loss of support from individual providers of capacity support and to the possibility of network overload if the supporting assets trip during a fault. There is also a risk of losing infeed to multiple providers of capacity support, due to a common mode failure (e.g. control system). This could cause problems on the distribution network or issues for the system operator in controlling frequency, due to the volume of infeed loss.

The volume of loss of support to be avoided following a common mode failure should be considered, to balance the potential risks, costs and impacts.

As storage (whether fixed or V2G from EVs) becomes more widespread there is likely to be an increase in the number of customers that can island from the network and maintain their own supply during interruptions. If this became widespread it may allow some upstream security of supply requirements to be relaxed.

Voltage

The requirements on distribution networks at customer connection points are defined in absolute terms in the ESQCRs. A more probabilistic approach to voltage limits could reduce reinforcement for extreme circumstances (e.g. infrequent back feed conditions). A further extension to a probabilistic approach would be an enhancement to customer products standards that automatically respond to voltage excursions.

Reactive power

There has been a well-documented reduction in reactive demand on distribution networks. This has caused issues for NESO in controlling voltage particularly at times of low demand. Two ways to assist could be:

- Define a reactive power envelope that the distributor needs to keep within at GSPs, or

- Ensure that the system operator has access to sources connected to the distribution network

A reactive power envelope would result in local requirements to each GSP to comply which might not be the most economic solution.

Ensuring access of embedded sources to NESO's reactive power markets would require ensuring that the reactive range of the embedded provider would not cause issues on the distribution network which could require reinforcement. The commercial arrangements for who pays for this work would need to be established.

In 2022, at the System Operators *'Future of Reactive Power Project Commercial and Technical Conclusions Workshop'* [40] the slide, displayed in Figure 11, was presented.

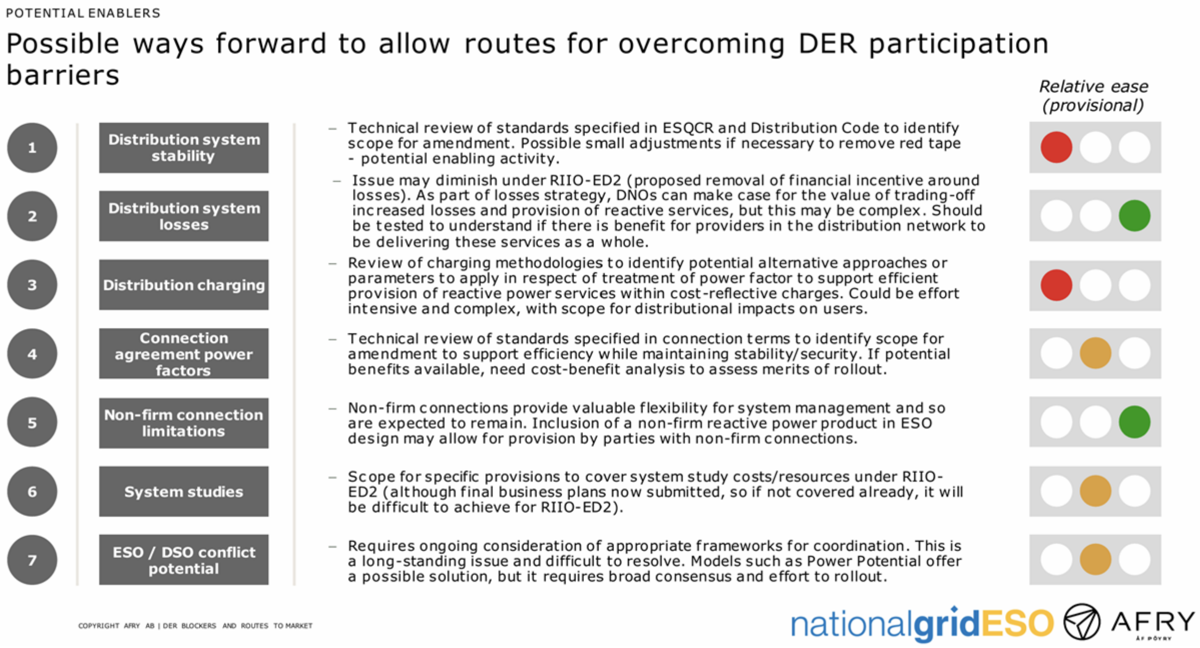

Figure 11: Output from system operators reactive power project technical and commercial workshop [40].

Whole-system alignment

Options for standards that set up clear accountability and responsibility

It is neither economically viable nor technically feasible to secure all risks to safeguard the supply security risk in electricity supply service, especially under extreme conditions. At present, these limits are not explicitly expressed in the standards. Standards help energy customers to understand the limits of electricity supply services and help them plan their own responses to extreme events emergencies. Standards should encourage customers responses, both in terms of operation and investment.

Options for achieving alignment between operating and planning standards

P2 has an established mechanism to account for DGs, energy storage and demand side responses at time of system peak. This has developed with limited flexibility markets, automation and digitalisation. As flexibility market continue to mature and expand to year-round conditions they will play a crucial role in manage both network capacity and voltage. This is likely to increase the value of customers flexibility. Increased operability and flexibility will allow DNOs to integrate greater volume of LCTs with reduced network investment, cutting down connection queues and promoting a green economy. Options include:

- Extending the standard for contribution of DGs, Energy Storage and Demand Responses from peak security to a limited set of year-round conditions when network security is at risk.

- Extending P2 from peak security for a given demand group (one-size-fit-all) to energy customers requiring differing supply reliability.
- Extending P2 from peak security to energy customers with differing supply reliability over a limited set of critical year-round conditions.

Current alignment between transmission and distribution networks

Distribution network standards have evolved to better reflect DG, ES and DSR for peak security and have several customer-facing and output-based standards to drive customer service performance, but do not have operation standards. Transmission network standards (SQSS) on the other hand remains an input-based standard, including both operation and investment, but have limited account for flexibility.

When major events happen, such as those on 9th August 2019, both transmission and distribution network resources will be impacted, and poor coordination could lead to uncoordinated action, especially in a system where system dynamics are increasing. As distribution networks take up more of the characteristics of transmission, there is both an opportunity and need for greater interaction. Options include:

- Aligning on the methodologies for the treatment of flexibility in transmission and distribution operating standards.
- Aligning on planning standards for determining peak and year-round conditions, the degree that DG and flexibility can substitute investment, and the balance between operating, planning and output standards.
- Aligning on operating standards to make the best use of existing assets from a greater understanding of resource and flexibility characteristics and coincidences.

5. Recommended next steps

Figure 12 shows the recommended next steps:

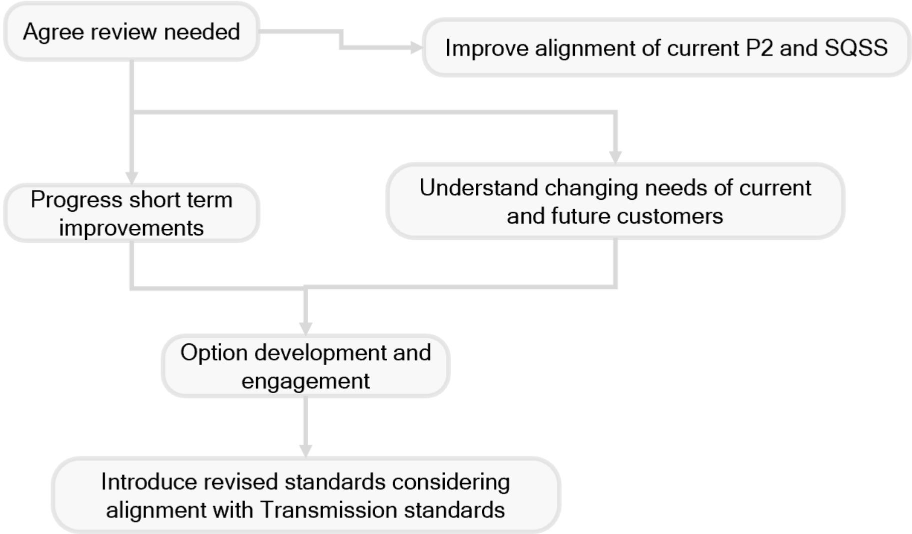

Figure 12: Recommended next steps

Short-term Improvements to Deterministic Planning Standards

The deterministic distribution security standard (P2) in GB is familiar to industry, easy to apply and simple for external bodies to verify compliance before or after an event. The assumption of demand and maximum demand however have not kept up with new technologies, digital innovation and emerging flexibility markets, which could distort the network's import/export requirements throughout the year. There are a number of potential changes that in the short term should be made to the current deterministic P2 standard:

- **Reassessment of the dominance test** that restricts the extent to which DG/DSR/ES can substitute for network assets is needed.
- Introducing an explicit requirement that network capacity under intact conditions is sufficient could enhance the availability of embedded flexibility to the System Operator.
- **Expressing demand groups in terms of number of customers** rather than peak demand in P2 could help to reduce distortion due to flexibility and local storage. Additional weighting would be introduced to differentiate customer classes and type of LCTs.

This would need development of the changes by DNO/DSOs, consultation with stakeholders and approval to changes to P2 by Ofgem with the consequential changes to the standard and Distribution Code.

Deeper Understanding of Customer Needs

To improve network standards, it is vital to understand the changing needs of current and future customers. Assessing these needs will help identify the best options to serve diverse stakeholders.

All electricity network companies undertake extensive stakeholder engagement as part of preparation for price controls. An analysis of these would be a good starting point to understand customer needs. This would highlight any missing stakeholder segments that engagement could be sought with.

It will be important to get views from a range of stakeholders including, domestic (both with and currently without EVs, electric heating, DG, storage), commercial DG and large scale storage, other utilities including telecommunications and NESO, local authorities, emergency services, SMEs and large industrial customers.

Option Development and Engagement

The options outlined in section 4 need to be developed into practical, implementable proposals to allow assessment of whether they meet the customer needs identified.

These options are:

- Improved deterministic standard
- Probabilistic standard
- Output standard
- Operating standard – including how to define and implement an operating envelope

Initial stakeholder engagement during the project there was majority support for a combination of customer facing output standards and network facing planning and operating standards. The response to the timescales on which change is needed was split between 1 to 3 years and 3 to 9 years.

Each of these options would need to consider the support available from DG/storage/DSR, the extent to which they would allow NESO access to flexibility and reactive power services that are embedded within the distribution network, and how better alignment can be achieve with the transmission SQSS standard.

The transition plan would be dependent on the degree of change from the current standard. Where significant change is involved, assessment of the degree of investment needed should be assessed to define a realistic transition period. In some cases, a 'grandfathering' approach may be needed where investment would only take place when triggered by another driver such as asset replacement. The process and timetable for change would need communication with all parties to ensure that they are prepared. Ongoing stakeholder input is essential for refining and testing these options.

Introducing Operating Standards

Current distribution standards were designed for a system when networks were largely build-and-forget, thus the focus has been on network planning, assuming peak demand represents the largest power imports/exports. Parts of the network already need active operation, however this is not universal nor are the processes and tools well developed. To move to an efficient, flexible and digitalised system, operational standards must be introduced swiftly to make a better use of existing network to deliver network efficiency, and greater use of growing customer assets.

Research needs to be undertaken to support the development of safe and efficient network operating envelopes. These need to consider system peaks, year-round conditions, and different parts of the network, where energy usage patterns and the penetration of LCTs, and VoLL varies. This will be further compounded by new flexibility markets being introduced to the system, together with the degree of coordination with central flexibility markets. It is crucially to have an open, transparent and interoperable modelling platform, allowing network operators and users to collectively design operating envelops that will best represent the network and customers' capability at a given time for safe and efficient operation of the whole-system.

Greater Alignment with Transmission Standards

In view of increasing converging system behaviours between distribution and transmission systems, greater alignment in planning, operation and performance standards will allow clean flexibility to seamless operate between the two systems, and achieve whole-system benefit to customers and net zero transition.

There is an urgent need to develop an alignment framework between the two systems to strike the balance between operation, planning and performance standards. The development should highlight standards that should converge over time, and standards that should differ to reflect the characteristics of networks and the needs of energy customers. Whilst this alignment is urgent, it may need change as detailed customer needs are understood.

Summary

1. Limitations of the current security-of-supply standards landscape

- **Homogenous customer assumptions:** Existing standards treat customers as broadly similar in terms of behaviour, flexibility, and the value placed on uninterrupted supply (VoLL).
- **Deterministic planning thresholds:** P2 uses fixed planning thresholds based on group peak demand to determine required network security.
- **Conservative treatment of flexible and distributed resources**: DR, storage, and DSR are recognised but their contribution to security is limited and conditional (e.g. the dominance test).
- **Underdeveloped voltage/reactive power rules:** Limited integration of voltage security and reactive power needs.
- **Separate standards:** Planning standards (e.g. P2, ETR 130) and output measures (e.g. IIS, WSC schemes) operate independently, rather than as an integrated whole-system framework.

2. Why change? Two structural shifts challenge these assumptions

Rising dependence on electricity across society:

- The electrification of heat, transport, and industrial processes increases both the criticality of supply and the magnitude of cold load pickup after outages.
- Digitalisation means loss of power now disrupts communications, payments, logistics and working patterns.

Transition to active, flexible distribution networks:

- These devices can shift demand, reduce peaks, and support the network via voltage and reactive power services.
- DER and customer flexibility introduce variability and uncertainty.

3. Potential options (high-level categories)

- **Output Standards (Customer-facing)** – Improve measurement of customer experience and reliability impacts (e.g., granular VoLL, updated IIS and customer service performance standards).
- **Planning Standards (Network-facing)** – Update and improve the current deterministic P2 standard. Convert to a probabilistic planning framework.
- **Operating Standards (Network-facing)** – Introduce a distribution operating standard that clarifies treatment of DG, storage, DSR, voltage, and reactive power.
- **Whole-system Standards** – Better align input-based and output-based standards, operation and planning standards and distribution and transmission standards.

4. Recommended next steps

- Short term improvements to deterministic planning standard – Reassessment of dominance test, explicit requirement that network capacity under intact conditions is sufficient and expressing demand groups in terms of customer numbers.
- Customer needs – understand the changing needs of current and future customers.
- Options development – develop options into practical and implementable proposals to allow assessment of whether they meet customer needs.
- Operating standard – develop safe and efficient network operating envelopes.
- Alignment with transmission standards – convergence of system behaviours requires alignment between distribution and transmission standards.

Some of the key benefits and issues for each main option, as well as the ease of transition, are shown in the table below:

Table 1: Summary of potential options to update the future distribution security of supply standards.

	Benefits	Issues	Ease of transition
Deterministic Standard	Transparent to stakeholders on network's import/export requirements from customer groups throughout the year. Easy for DNO to apply.	Redundancy level depends only on a group Does not use a consistent VoLL across groups	Changes would be an evolution from current
Probabilistic Standard	Network tailored to VoLL from customer surveys	Lacks transparency to stakeholders Different outcomes for different customers Dependent on the estimate of VoLL	Difficult, transition arrangements would be needed probably over several years
Output Standard	Focus on outcomes for customers. Deeper understanding of different customer needs for supply security. Incentivising targeted network interventions to deliver benefits for energy customers.	Difficult to design network to ensure compliance without further standards	Straight forward
Operating Standard	Gives a year-round standard for risk to network potentially releasing additional network capacity from existing network.		Likely to be an evolution from current practices
Extended Voltage Standard	Avoids reinforcement where risk is very low reducing network costs.	Firm evidence of lack of risk	Depends on legislative change
Var provider access to SO	Increases options for SO to control transmission voltage enhancing collaboration between SO and DNOs	Agreement on who pays for any necessary reinforcement	Difficult due to needing to agree commercial arrangements
Harmonic standard	Ability to connect more invertor-based resources quickly	Agreeing funding arrangement	Difficult as funding arrangement would need to be established

References

[1] "IEEE Guide for Electric Power Distribution Reliability Indices," *IEEE Std 1366-2022 (Revision of IEEE Std 1366-2012),* pp. 1-44, 2022.

[2] Energy Networks Association, "Engineering Recommendation P2 Issue 8 2023," 2023. [Online]. Available: https://dcode.org.uk/assets/uploads/files/ENA_EREC_P2_Issue%208_(2023).pdf. [Accessed 12 December 2025].

[3] Energy Networks Association, "Engineering Report 130 Issue 4 2023," 2023. [Online]. Available: https://dcode.org.uk/assets/uploads/files/ENA_EREP_130_Issue%204_(2023).pdf. [Accessed 12 December 2025].

[4] Energy Networks Association, "Engineering Recommendation P2 Issue 6 2006," 2006. [Online]. Available: https://dcode.org.uk/assets/uploads/ENA_ER_P2_Issue_6__2006_-1.pdf. [Accessed 12 December 2025].

[5] Energy Networks Association, "Engineering Report 130 Issue 1 2006," 2006. [Online]. Available: https://www.ena-eng.org/ena-docs/Index?Action=ViewDetail&EID=96453&PEID=96477. [Accessed 12 December 2025].

[6] Energy Networks Association, "Engineering Recommendation P2 Issue 7 2019," 2019. [Online]. Available: https://dcode.org.uk/assets/files/Qualifying%20Standards/ENA_EREC_P2_Issue%207_(2019).pdf . [Accessed 12 December 2025].

[7] Energy Networks Association, "Engineering Report 130 Issue 3 2019," 2019. [Online]. Available: https://dcode.org.uk/assets/files/Qualifying%20Standards/ENA_EREP_130_Issue%203_(2019).pdf . [Accessed 12 December 2025].

[8] UK Government, "The Electricity Safety, Quality and Continuity Regulations 2002," 2002. [Online]. Available: https://www.legislation.gov.uk/uksi/2002/2665. [Accessed 12 December 2025].

[9] UK Government, "Electricity Act 1989," 1989. [Online]. Available: https://www.legislation.gov.uk/ukpga/1989/29/contents. [Accessed 12 December 2025].

[10] Department of Trade and Industry, "GUIDANCE ON THE ELECTRICITY SAFETY, QUALITY AND CONTINUITY REGULATIONS 2002," 2002. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/82784/GuidElectSafety_Quality.pdf.

[11] Ofgem, "Guarenteed Standards of Performance Update 2025," 2025. [Online]. Available: https://www.ofgem.gov.uk/sites/default/files/2025-03/Guarenteed-Standards-of-Performance-Update-2025.pdf . [Accessed 12 December 2025].

[12] UK Government, "The Electricity at Work Regulations 1989," 2989. [Online]. Available: https://www.legislation.gov.uk/uksi/1989/635/contents . [Accessed 12 December 2025].

[13] Ofgem, "RIIO-ED2 Regulatory Instructions and Guidance – Interruptions," 2024. [Online]. Available: https://www.ofgem.gov.uk/sites/default/files/2024-01/RIIO-ED2%20-%20Annex%20F%20Interruptions%20v1.1.pdf . [Accessed 12 December 2025].

[14] London Economics, "The Value of Lost Load (VoLL) for Electricity in Great Britain," 2013. [Online]. Available: https://www.ofgem.gov.uk/sites/default/files/docs/2013/07/london-economics-value-of-lost-load-for-electricity-in-gb_0.pdf . [Accessed 12 December 2025].

[15] Ofgem, "ED3 Sector Specific Methodology Consultation," 2025. [Online]. Available: https://www.ofgem.gov.uk/sites/default/files/2025-10/ED3-sector-specific-methodology-consultation-core-document_clean.pdf. [Accessed 12 December 2025].

[16] Ofgem, "RIIO-ED2 Final Determinations Core Methodology Document - Chapter 6," 2022. [Online]. Available: https://www.ofgem.gov.uk/sites/default/files/2022-11/RIIO-

ED2%20Final%20Determinations%20Core%20Methodology.pdf. [Accessed 12 December 2025].

[17] Ofgem, “Join your supplier’s Priority Services Register,” [Online]. Available: https://www.ofgem.gov.uk/information-consumers/energy-advice-households/join-your-suppliers-priority-services-register. [Accessed 12 December 2025].

[18] “National Electricity Transmission System Security and Quality of Supply Standard Version 2.10,” 2025. [Online]. Available: https://www.neso.energy/document/358751/download . [Accessed 12 December 2025].

[19] UK Government, “Energy Act 1976,” 1976. [Online]. Available: https://www.legislation.gov.uk/ukpga/1976/76/contents. [Accessed 12 December 2025].

[20] Ofgem, “Transporter Standard Licence Conditions,” 2024. [Online]. Available: https://epr.ofgem.gov.uk/c/xy42ijGNQHGZlwVFYcixCw/p/b30b97ae-de90-43e3-9526-3833c110b0fe/wvp/a792b684-413e-4535-b454-76ff5c64dd4a. [Accessed 12 December 2025].

[21] Working Group 1 , “SQSS Fundamental Review,” 2009. [Online]. Available: https://www.neso.energy/document/14856/download. [Accessed 12 December 2025].

[22] AGENCY FOR THE COOPERATION OF ENERGY REGULATORS, “STUDY ON THE ESTIMATION OF THE VALUE OF LOST LOAD OF ELECTRICITY SUPPLY IN EUROPE,” 2018. [Online]. Available: https://www.acer.europa.eu/sites/default/files/documents/en/Electricity/Infrastructure_and_network%20development/Infrastructure/Documents/CEPA%20study%20on%20the%20Value%20of%20Lost%20Load%20in%20the%20electricity%20supply.pdf. [Accessed 12 December 2025].

[23] The Brattle Group, “Approaches to setting electric distribution reliability standards and outcomes,” 2012. [Online]. Available: https://www.brattle.com/wp-content/uploads/2017/10/6384_approaches_to_setting_electric_distribution_reliability_standards_and_outcomes_hesmondhalgh_zarakas_brown_jan_2012.pdf. [Accessed 12 December 2025].

[24] UK Department for Transport, “Vehicle licensing statistics data tables,” 2025. [Online]. Available: https://www.gov.uk/government/statistical-data-sets/vehicle-licensing-statistics-data-tables. [Accessed 12 December 2025].

[25] Statista, “Percentage of households with central heating systems in the United Kingdom (UK) from 1970 to 2018,” 2025. [Online]. Available: https://www.statista.com/statistics/289137/central-heating-in-households-in-the-uk/?srsltid=AfmBOooHecrpnI3nERj07BwlLZzIs2n6IU1eiusb6_GDpSPZmOQymjo5. [Accessed 12 December 2025].

[26] Office for National Statistics, “Main fuel type or method of heating used in central heating, England and Wales,” 2025. [Online]. Available: https://www.ons.gov.uk/peoplepopulationandcommunity/housing/datasets/mainfueltypeormethodofheatingusedincentralheatingenglandandwales. [Accessed 12 December 2025].

[27] Electricity North West, “ENWL 021,” 2021. [Online]. Available: https://smarter.energynetworks.org/projects/enwl-021/. [Accessed 12 December 2025].

[28] Department of Energy and Climate Change, “Annex C: Reliability Standard Methodology,” 2013. [Online]. Available: https://assets.publishing.service.gov.uk/media/5a7c52eaed915d338141e0ce/emr_consultation_annex_c.pdf. [Accessed 12 December 2025].

[29] National Infrastructure Commission, “Electricity distribution networks: Creating capacity for the future,” 21 February 2025. [Online]. Available: https://webarchive.nationalarchives.gov.uk/ukgwa/20250327100350/https:/nic.org.uk/studies-reports/electricity-distribution-networks-report/. [Accessed 9 December 2025].

[30] Department for Energy Security and Net Zero, “Electricity Distribution Networks study: government response,” 7 July 2025. [Online]. Available:

https://www.gov.uk/government/publications/electricity-distribution-networks-study-government-response. [Accessed 9 December 2025].

[31] "IEEE Guide for Distributed Energy Resources Management Systems (DERMS) Functional Specification," *IEEE Std 2030.11-2021,* pp. 1-61, 2021.

[32] "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," *IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003),* pp. 1-138, 2018.

[33] "IEEE Guide for Identifying and Improving Voltage Quality in Power Systems," *IEEE Std 1250-2018 (Revision of IEEE Std 1250-2011),* pp. 1-63, 2018.

[34] "IEEE Guide for Transformer Loss Measurement," *IEEE Std C57.123-2019 (Revision of IEEE Std C57.123-2010,* pp. 1-55, 2020.

[35] Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy, "Electrical engineering standards: independent review," 23 July 2019. [Online]. Available: https://www.gov.uk/government/publications/electrical-engineering-standards-independent-review. [Accessed 9 December 2025].

[36] Council for Science and Technology, "Electricity supply: economic and social costs of electricity shortfalls," 27 November 2014. [Online]. Available: https://www.gov.uk/government/publications/electricity-supply-economic-and-social-costs-of-electricity-shortfalls. [Accessed 9 December 2025].

[37] Smartgrids Security and Resilience Task Force, "The need for a fundamental review of electricity networks reliability standards," 2016. [Online]. Available: https://smart-networks-energy-transition.ec.europa.eu/sites/default/files/publications/ETP_SG_Future_Network_Reliability_Standards_2016.pdf. [Accessed 9 December 2025].

[38] London Economics, "The Value of Lost Load (VoLL) for Electricity in Great Britain," July 2013. [Online]. Available: https://londoneconomics.co.uk/blog/publication/the-value-of-lost-load-voll-for-electricity-in-great-britain/. [Accessed 9 December 2025].

[39] G. Lankeshwara, R. Sharma, R. Yan, W. Tushar and T. K. Saha, "A review on network-aware control of distributed energy resources under the dynamic operating envelopes framework," *Renewable and Sustainable Energy Reviews,* vol. 217, 2025.

[40] National Grid ESO, "Future of Reactive Power Project Commercial and Technical Conclusions Workshop," 2022. [Online]. Available: https://www.neso.energy/document/244996/download. [Accessed 12 December 2025].